Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **23,** 1101–1121 (1998)

THE DISTRIBUTION OF LARGE WOODY DEBRIS ACCUMULATIONS AND POOLS IN RELATION TO WOODLAND STREAM MANAGEMENT IN A SMALL, LOW-GRADIENT STREAM

A. M. GURNELL AND R. SWEET

School of Geography, University of Birmingham, Birmingham B15 2TT, UK

Received 12 January 1998; Revised 10 June 1998; Accepted 1 July 1998

ABSTRACT

This paper focuses upon the natural dynamics of large woody debris (LWD), the impact of management on LWD dynamics, and the impact of LWD removal and channelization on the distribution and size of pools in a British, second to third order, headwater catchment. The study stream is rather different from those subject to LWD accumulations which have been studied in North America. The most important contrast is that it is surrounded by predominantly deciduous rather than coniferous woodland. In terms of its width (1·8–4·5m) and gradient (0·013m m^{-1}), it falls within the lower range of channels studied in North America. Nevertheless, there are similarities in LWD dam and pool spacing with some North American studies. The information on LWD dynamics during a period without management and on recovery of LWD dams after clearance covers a 16 year period (1982–1997). The paper illustrates that seven to eight years after clearance the total number of LWD dams has recovered but the most hydraulically active dam type has not recovered to pre-clearance levels. An analysis of geomorphological maps of the channel surveyed in 1982 and 1996/97 shows an overall decrease in the number and size of pools along the section that was cleared of LWD dams. The magnitude of the decrease and the associated adjustments in pools through changes in their size and location differ according to location with respect to a section of the study stream which was channelized in *c*. 1966 and which has subsequently incised its bed. © 1998 John Wiley & Sons, Ltd.

KEY WORDS large wooody debris; pools; river channelization

INTRODUCTION

Large woody debris and woodland river environments

Recent reviews (e.g. Gurnell *et al*., 1995; Maser and Sedell, 1994; Sullivan *et al*., 1987), based mainly upon research undertaken in North America, show that large woody debris (LWD) accumulations are of value for woodland river environments, enhancing biological diversity and productivity, regulating flows and water quality, and increasing the range of habitats within and along the river. Specifically, LWD affects woodland river environments in four main ways.

1. LWD directly impinges upon the hydrology (MacDonald *et al*., 1982) and hydraulics (Ehrmann and Lamberti, 1992; Marston, 1982) of in-channel and streambed flows (Thibodeaux and Boyle, 1987); of river – floodplain–alluvial aquifer interactions including the distribution and intensity of overbank (Hickin, 1984) and underbank (Harvey and Bencala, 1993) flows; and of subriparian flowpaths (Harvey and Bencala, 1993).
2. As a result of these hydrological and hydraulic effects, LWD accumulations affect the transport and storage of solutes, sediments and organic material within the river channel system and floodplain

* Correspondence to: Prof. A. M. Gurnell, School of Geography, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

CCC 0197-9337/98/121101–21 $17.50

(Hedin *et al.*, 1988; Keller and Swanson, 1979; Keller and Tally, 1979; Lisle, 1981) so that river channels attenuate the downstream transfer of solutes, sediments and organic material.

3. Influences on flow hydraulics and sediment storage and transport lead to secondary impacts on the geomorphology of woodland river channels including the average condition and variance in channel dimensions (Hogan, 1986; Keller and Swanson, 1979; Nakamura and Swanson, 1993); the size and distribution of pools and riffles (Andrus *et al.*, 1998; Bisson *et al.*, 1982, 1987; Robison and Beschta, 1990a,b); and the overall stability of river channels (Bilby, 1984; Heede, 1985; Marston, 1982). Thus woodland rivers affected by LWD accumulations consist of channels which present a high physical habitat diversity both within and between debris accumulations (Angermeier and Karr, 1984; Benke *et al.*, 1985; Marzolf, 1978).
4. The complex physical structure of woodland rivers, and particularly of LWD accumulations, provides a variety of habitat patches which can support a wide range of organisms at different stages of their life cycles (Bisson and Sedell, 1984; Scrivener and Anderson, 1984; Smock *et al.*, 1992), and LWD may have an important role in regulating water quality and in sustaining refuge habitats to protect biota during pollution episodes and high flows. Furthermore, the storage, breakdown and regulated release of organic matter within LWD accumulations provide temporally and spatially regulated food sources for aquatic biota (Anderson and Sedell, 1979; Smock *et al.*, 1992; Ward and Aumen, 1986; Winkler, 1991).

River corridors are important for the conservation of biodiversity at the landscape scale. LWD is an important component of stream ecosystems within natural forest catchments. In North America, research results have been adopted by river managers such that wood is deliberately emplaced in some streams and active management of streamside woodland buffer strips is encouraged to supply woody debris to the river (Sedell and Swanson, 1984). However, little research has been undertaken on the role of LWD in European rivers. Moreover, studies that have been undertaken (e.g. in the UK and France: Gregory, 1992; Gurnell and Gregory, 1995; Piégay and Gurnell, 1997) demonstrate subtle differences in the nature and role of LWD as a result of: (a) climatic contrasts with the areas in which the majority of the research has been undertaken in North America (Alaska, Pacific Northwest, Florida, California and N. Carolina); (b) contrasts in tree species including the significance of the slow decay rates of some North American tree species; and, most importantly, (c) differences in the degree and nature of forest and riparian woodland management practices, and (d) differences in the scale and level of management of river systems.

The association between LWD and pools

The pool–riffle sequence forms a fundamental geomorphological unit in many types of river channel. A widely reported range in the average spacing of pool and riffle units (five to seven channel widths) is based on proposals by Leopold and Wolman (1957) and Leopold *et al.* (1964), although recent reviews (Ward *et al.*, 1995; Brookes, 1995; Gregory *et al.*, 1994) quote a wider range of spacings. Of particular relevance to the present discussion is the observation by Gregory *et al.* (1994) that smaller average spacings than five to seven channel widths had been reported for unmanaged channels as a result of the influence of large organic debris. This is confirmed by the extensive analysis of forested channels in Alaska and Washington by Montgomery *et al.* (1995) who note that ‘pool spacing in forest channels of mountain drainage basins is controlled by LWD loading and channel type, slope and width... Mean pool spacing in forest pool–riffle channels is less than expected for free-formed pool riffle reaches, primarily owing to local flow convergence and bed scour associated with LWD’ (p. 1104). Montgomery *et al.* (1995) found pool spacings ranging from 0·2 to 13 channel widths in a sample of forest channels. Spacing was closest in forced pool–riffle channels (i.e. pool–riffle channels ‘where more than half of the pools are forced by flow convergence, divergence and turbulent scour associated with in-channel obstructions’), ranging from 0·2 to three channel widths with the lowest values associated with the highest debris loadings.

The increased frequency of pools in channels affected by LWD results from the hydraulic influence of the LWD (e.g. Smith and Beschta, 1994). Bisson *et al*. (1982, 1987) developed a classification of pools, riffles and glides that are relevant to fish habitat; and of 10 pool types, six were associated with woody debris (backwater, dammed pool, plunge pool, lateral scour pool associated with LWD; backwater, lateral scour pool associated with root wad). This close association between LWD and specific types of pool helps to explain why Wood-Smith and Buffington (1996) found pool spacing and pool depth to be the two best geomorphological discriminators between pristine forest streams and streams influenced by timber harvesting in Alaska.

A contribution to research on LWD in European headwater rivers

This paper compiles and analyses a series of field surveys undertaken at different dates over the last 16 years to provide a contribution to research on the role of LWD in European headwater rivers. It considers the impact of the recent history of management of a small river draining a catchment in the New Forest, Hampshire, UK. It focuses upon the natural dynamics of LWD, the impact of management on LWD dynamics, and the apparent impact of LWD removal and river channelization on the distribution and size of pools, a key geomorphological element within headwater rivers.

Since stream order is frequently used as a scaling factor in the LWD literature, it is necessary to use it here in order to draw comparisons with other studies. However, channel width is also used wherever possible because it is a more informative metric. It not only clarifies the precise size of the channel but it is also highly correlated with parameters of the transmitted flow regime (e.g. Wharton, 1995).

THE STUDY AREA

The distribution and dynamics of LWD accumulations have been the focus of research within the Highland Water catchment since the early 1980s (e.g. Gregory and Davis, 1992; Gregory *et al*., 1985, 1993, 1994; Gurnell and Gregory, 1987, 1995). The New Forest is one of the few areas within the UK where woodland river channels remain relatively unmanaged. As a result, it has been possible to study the distribution and character of LWD accumulations and the geomorphology of headwater river channels in a relatively natural state under a mixed, but mainly deciduous, woodland cover. Furthermore, where management has occurred, it has been possible to isolate its timing and nature so that the response of the river system to particular types of management could be defined.

Figure 1A illustrates the distribution of woodland and heathland within the Highland Water catchment. Figure 1B locates the five channel sectors (A to E) that are discussed in this paper. Streams within all five sectors flow through mixed clay, silt and gravel alluvial deposits, along a valley gradient of approximately $0{\cdot}013\,\mathrm{m\,m^{-1}}$. Based on the stream network represented on 1:25000 scale Ordnance Survey maps, sectors A and B are second order and sectors C, D and E are third order. Table I provides information on the characteristics of each of the five sectors. Table I also indicates that there have been two management impacts on the river system: channelization or straightening of the channel at different dates along sectors C and D (the more recent channelization of sector C during the 1960s was associated with the planting of coniferous trees); and LWD clearance in sectors B to E, mainly during 1989. The influence of both of these practices on the distribution and dynamics of LWD accumulations and their apparent relationship with the distribution and size of pools is explored by aggregating information for 100m reaches of the five sectors. In the following analyses sectors A to E include 100m reaches of channel numbered –10 to –6 and –4 to –3 (sector A); 1 to 14 (sector B); 15 to 22 (sector C); 23 to 44 (sector D) and 45 to 52 (sector E). Sector A is used in the following analyses to represent an unmanaged situation. As a result, reaches –2 to –1 are excluded because they are immediately upstream of a road bridge and have been subject to frequent LWD disturbance and removal in recent years. Reach –5 is also excluded because it includes a footbridge around which the stream, including the dams, has been frequently disturbed by children playing.

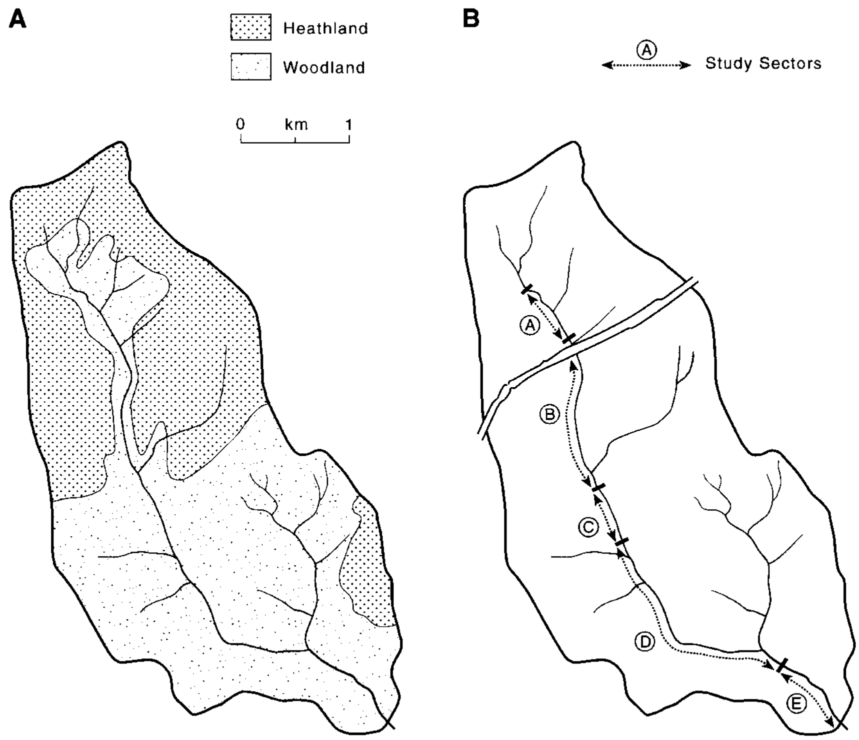

Figure 1. The Highland Water catchment: (A) distribution of woodland and heathland; (B) the study sectors

LWD DISTRIBUTION AND DYNAMICS

Figure 2 illustrates the frequency of LWD accumulations or dams within each of the 100m stretches of the five study sectors in 1982 in comparison with 1984 (a period unaffected by LWD management) and 1996/97 (after the removal of dams throughout sectors B to D in 1989–1992). Two properties of Figure 2 are noteworthy. First, in both of the graphs, reaches 15 to 22 of sector C, the most recently channelized sector, and the upstream reaches within sector D contain very few debris accumulations in comparison with other reaches. Second, with the exception of sector C, there appears to be a decreasing number of debris accumulations within the 100m reaches in a downstream direction (i.e. in the direction of increasing reach number).

Gregory *et al.* (1985) produced a simple classification of LWD dams to reflect their relative hydraulic influence. Active dams completely span the channel and cause a step in the water surface profile, even at low flows; complete dams span the channel but are sufficiently leaky to have no noticeable effect on the low flow water surface profile; and partial dams do not completely span the channel. Whilst all dams impact on flow hydraulics and thus on sediment storage and transfer and on channel morphology, it is the active dams which are likely to have the greatest influence, because of their noticeable effect on the energy gradient at all flow stages, whereas partial dams are likely to be least influential.

Table II shows the changes in the total frequency of dams and in the frequency of dams of differing type within the five sectors from the 1982, 1984 and 1996/97 surveys. The data illustrate a trend of increasing dam spacing downstream, with the exception of C, the channelized sector. Sector C does not retain LWD accumulations at any of the survey dates, having a very low average frequency of dams in comparison with the other sectors, and an almost total absence of complete and active dams.

The consequences of debris dam clearance (in 1989 or 1992, see Table I), and of the subsequent

Table I. Characteristics of the five study sectors, A–E

	A	B	C	D	E
Average bankfull channel width (m)	1·8	2·4	2·5	4·0	4·5
Sector length (m)	700	1400	800	2200	800
Marginal woodland type	Mixed deciduous	Mixed deciduous	Coniferous plantation	Mixed deciduous	Mixed deciduous
Management history	No recent management known	1989 debris dam clearance	c. 1966 channelization	1989 debris dam clearance Early channelization (> 80 years ago?) of much of the sector	1989 debris dam clearance of upstream 600 m, 1992 debris dam clearance of downstream 200 m
Data sets analysed	1982, 1984, 1996, 1997 debris dam surveys	1982, 1984, Jan. 1990, July 1990, Nov. 1990, May 1991, May 1996 debris dam surveys	1982, 1984, Jan. 1990, July 1990, Nov. 1990, May 1991, May 1997 debris dam surveys	1982, 1984, Jan. 1990, July 1990, Nov. 1990, May 1991, May 1996 debris dam surveys	1982 (downstream 300 m surveyed Jan. 1983), 1984 (600 m only), Jan. 1990, July 1990, Nov. 1990, May 1991, May 1996 debris dam surveys
	1997 geomorphological maps	1982, 1996 geomorphological maps	1982, 1997 geomorphological maps	1982, 1996 geomorphological maps	1982 (downstream 300 m surveyed Jan. 1983), 1996 geomorphological maps

recovery of LWD accumulations are detailed in Figures 3 and 4. Figure 3 depicts the change in total dam frequency in reaches 1 to 52 (sectors B, C, D and E) at each survey date in comparison with 1982. The vertical bars represent the survey date dam frequency in each 100 m reach substracted from the 1982 dam frequency, so that positive values indicate less dams and negative values more dams than were observed in 1982. The 1984 survey shows the small positive and negative changes that represent a period of natural adjustment, when debris was not managed. The large positive values for January 1990 illustrate the enormous decrease in dams as a result of dam clearance in sectors B to E during late 1989, whereas the absence of bars in sector C reflects the fact that there were very few dams in this sector before or after clearance was undertaken. By July 1990, two lengths of the channel exhibit negative values (an increase in dam frequency in comparison with 1982): sector C, indicating that the channelized section is accumulating debris; and the downstream part of sector E, indicating that debris mobilized by dam removal upstream is becoming trapped in the section that was not cleared until 1992. It should be noted that in addition to debris clearance, there was a major wind storm immediately after the January 1990 survey, which introduced much LWD into the channel. Significant tree fall also occurred during the storm, but the trees mainly bridged the channel (Gregory, 1992) and the majority were subsequently cut up and removed. By the November 1990 survey, the new dams in sectors C and E had disappeared, leaving an overall reduction in the number of dams in comparison with 1982, but the deficit was less marked than in January 1990, immediately after clearance. May 1991 saw a further reduction in the overall deficit of dams in comparison with 1982, with a few reaches actually containing more dams than in 1982. By May 1996, the overall total of dams was greater than in 1982, with no clear downstream pattern in reaches retaining either a greater or smaller number of dams.

Figure 4 illustrates the response of the three classes of dam to clearance. Partial dams follow a very similar pattern of recovery to that described above for total dams. The only major difference is the

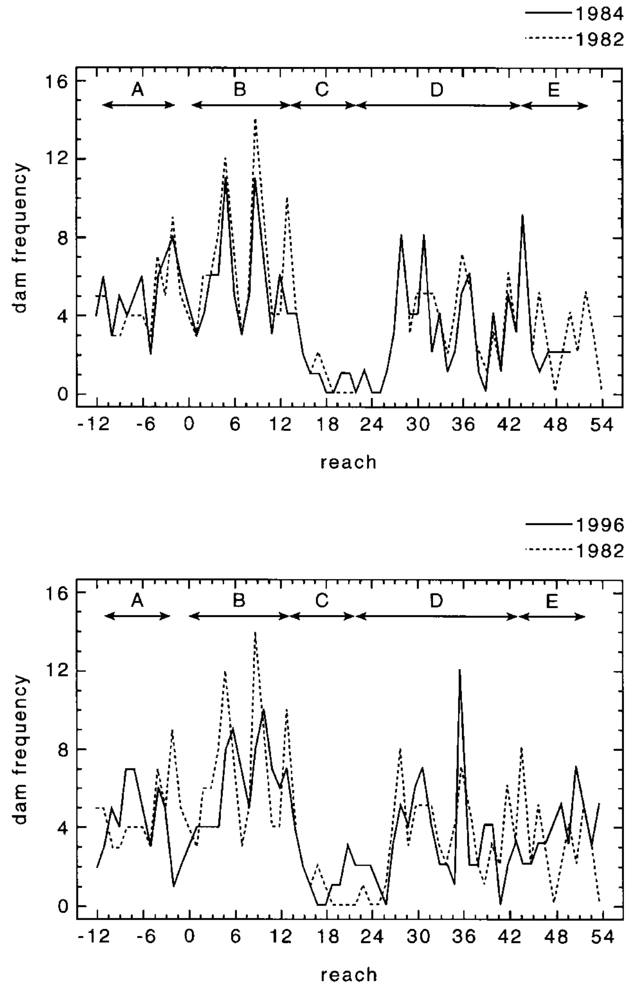

Figure 2. Frequency of LWD dams in each 100 m reach in sectors A to E in 1984 (upper graph) and 1996 (lower graph) in comparison with 1982. Sector C data are for 1997

considerably larger number of partial dams present throughout the river length in 1996 in comparison with 1982. By 1996, complete dams appear to have recovered to approximately their pre-clearance frequency, but the overall frequency of active dams is still relatively low. Thus, although the total number of dams in 1996 is greater than that in 1982, the hydraulically important active dams have not recovered. The clusters of dams that appeared in sectors C and E in the July 1990 survey and then disappeared by the November 1990 survey were mainly partial dams, a smaller number were complete dams but none were active dams. This illustrates that in the absence of major active dams, LWD is very mobile. Complete and active dams are important influences on debris mobility, and are also highly significant for the retention of other organic matter and mineral sediment.

Figures 3 and 4 illustrate a considerable recovery of LWD accumulations in the seven years after clearance, although the relatively low proportion of active dams may indicate that recovery is still not complete. Nevertheless, Table II shows that in the unmanaged sector (A) the number of active debris dams in 1996 is only 66 per cent of the number in 1982. This change may reflect the impact of much

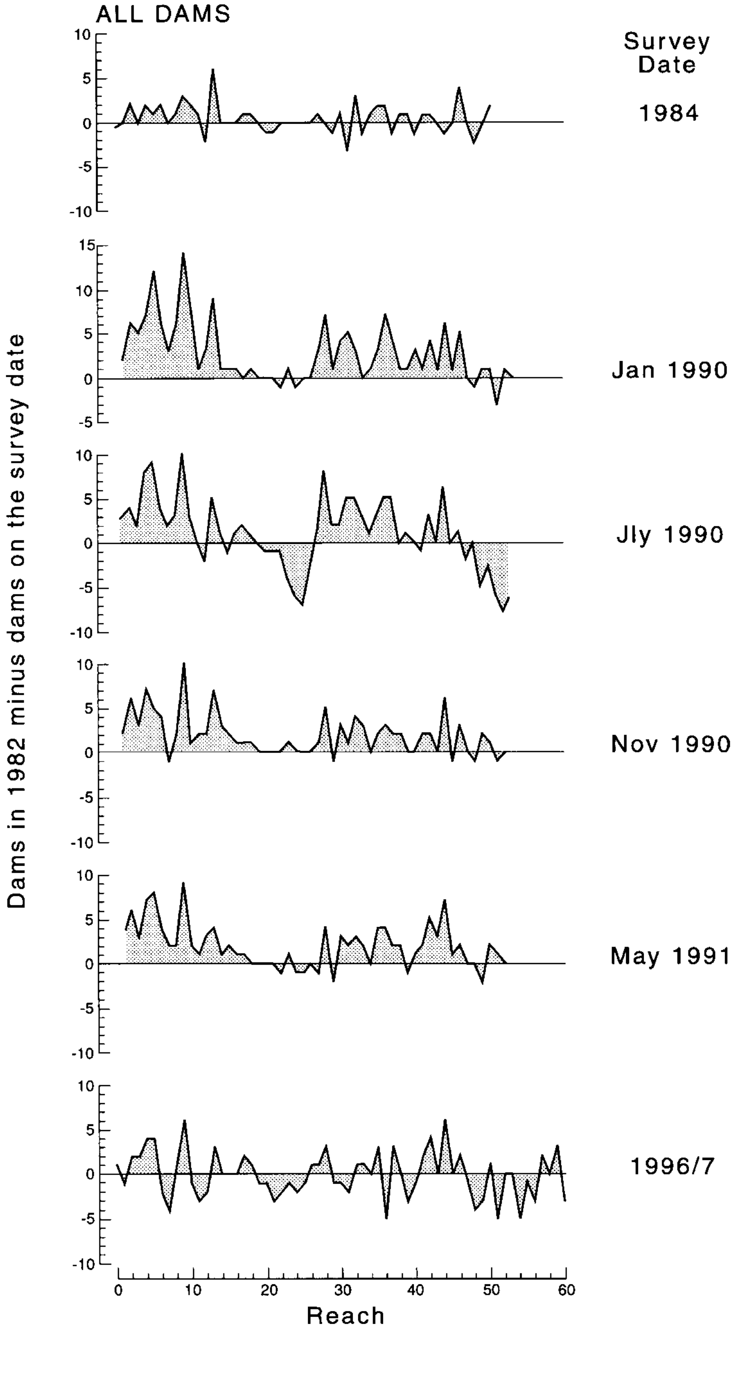

Figure 3. Total dams in each 100 m reach in 1982 minus total dams in the same reaches in 1984, January 1990, July 1990, November 1990, May 1991 and 1996 (1997 for sector C)

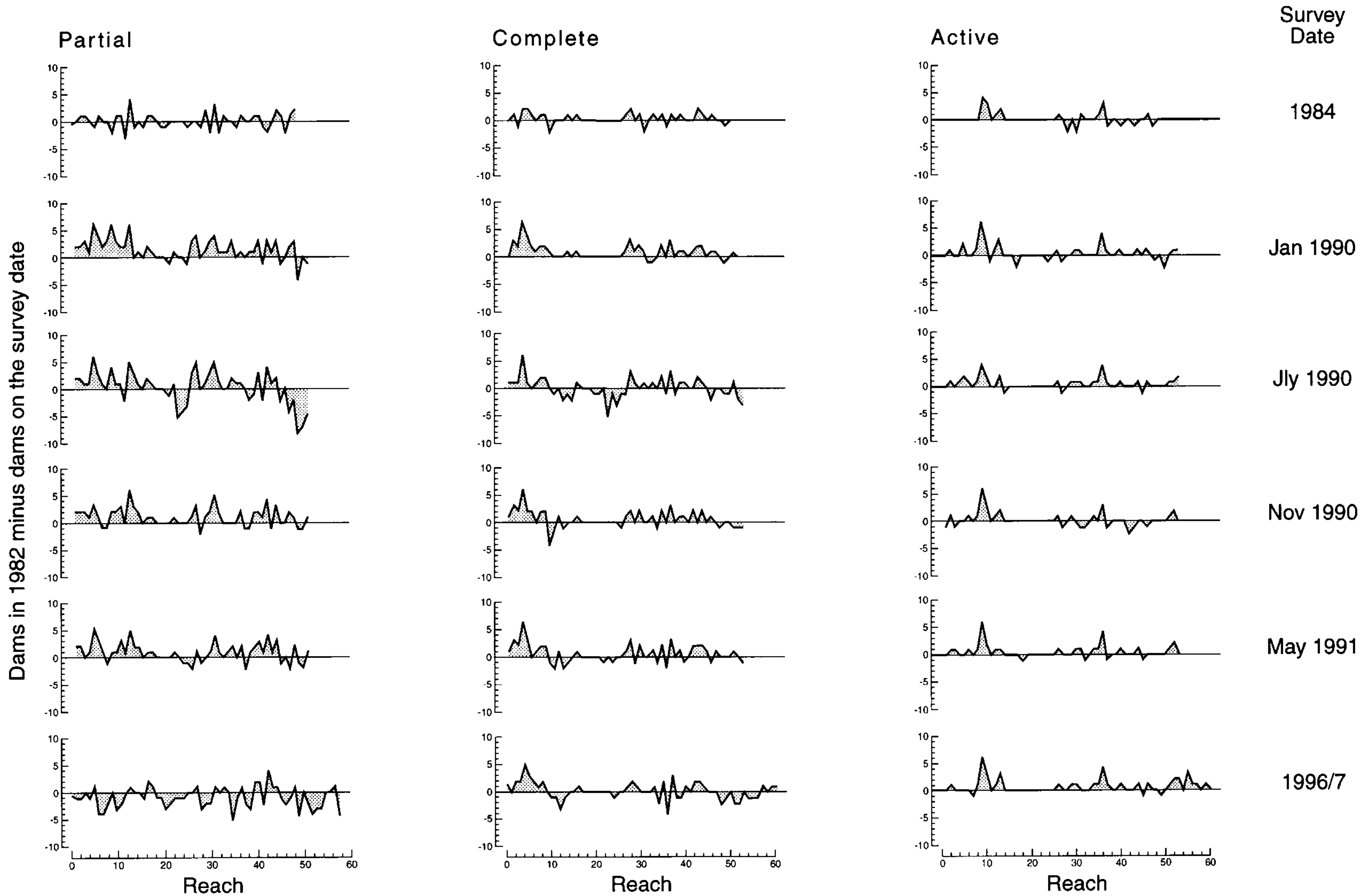

Figure 4. The frequency of partial dams, complete dams and active dams in each 100 m reach in 1982 minus partial, complete and active dams, respectively, in the same reaches in 1984, January 1990, July 1990, November 1990, May 1991 and 1996 (1997 for sector C)

Table II. Average dam frequency per 100 m reach (to one decimal place) within the five channel sectors: 1982, 1984 and 1996/97

	A	A	B	C	D	E
1982						
Total dams		4·3	6·9	0·8	3·5	2·8
Partial dams		1·9	3·5	0·6	2·0	1·8
Complete dams		1·1	1·9	0·1	1·0	0·5
Active dams		1·3	1·5	0·0	0·6	0·5
Active + complete dams		2·4	3·4	0·1	1·6	1·0
1984						
Total dams		5·1	5·6	0·8	3·3	1·8
Partial dams		1·6	3·6	0·8	2·0	1·2
Complete dams		1·9	1·4	0·0	0·6	0·5
Active dams		1·7	0·8	0·0	0·6	0·2
Active + complete dams		3·6	2·2	0·0	1·3	0·7
1996/97	1997	1996	1996	1997	1996	1996
Total dams	6·6	5·6	6·2	1·3	3·2	4·0
Partial dams	4·3	3·1	4·6	1·3	2·5	2·4
Completed dams	1·6	1·6	1·1	0·0	0·7	1·4
Active dams	0·7	0·9	0·5	0·0	0·0	0·3
Active + complete dams	2·3	2·4	1·6	0	0·7	1·6
Active + complete 1996: active + complete 1982		1·00	0·47	0·0	0·46	1·63
Active 1996: active 1982		0·66	0·33	–	0·08	0·5

The 1984 survey only included the upstream 600 m of sector E

lower flows during the recent (1988–1996) period than was previously experienced. Such low flows in headwater streams would be unable to move the larger debris pieces which form the key pieces for active debris dams; meanwhile decomposition of LWD may result in the failure or partial failure of pre-existing active dams. This conclusion is reinforced by the stability in the total of complete and active dams in sector A between 1982 and 1996, and by the fact that a detailed analysis of dam location and type suggests that changes in complete and active dams in sector A over 14 years were achieved by a change in dam class rather than by dam creation or removal in over 50 per cent of cases. This contrasts with partial dams where over 80 per cent of changes resulted from creation of new dams or complete removal of old dams. Similar conclusions can be drawn by comparing the 1982 with the 1997 data for sector A. In sectors B, D and E there are substantially fewer active dams in 1996 in comparison with 1982 (33 per cent, 8 per cent and 50 per cent respectively), and although the total of complete and active dams in sector E exceeds that in 1982, sectors B and D remain in deficit. This decline in the hydraulically important complete and active dams, particularly in sectors B and D, further indicates that LWD accumulations are still recovering from the 1989 clearance in spite of the storm inputs of 1990.

POOLS

Downstream plunge pools, upstream dammed pools, lateral pools (particularly those associated with flow constriction by partial dams and underflows through complete and active dams) and accumulations of mineral sediment are characteristic geomorphological features associated with LWD accumulations. The removal of debris dams releases the stored sediment and also removes a major stepped control on the channel long profile and thus on local base levels (Beschta, 1979; Klein *et al*., 1987; MacDonald and

Keller, 1987; Megahan, 1982; Smith *et al.*, 1993).

It is clear from field inspection of sector C that considerable erosion of the channel bed has occurred recently (up to 0·3m in some places, as revealed by the freshly eroded, unweathered material exposed at the base of the banks). It is also clear from the plumes of fresh bed sediment, particularly at the upstream end of many pools, that sediment is mobile within sectors B, C, D and E, whereas such sediment plumes are not widespread in sector A. No quantitative data are available to underpin these observations, but two geomorphological maps of the channel through sectors B, C, D and E for 1982 and 1996 (1997 for sector C) provide the basis for evaluating geomorphological change. Unfortunately, no geomorphological survey of sector A was undertaken in 1982. However, the sector was surveyed in 1997, so providing comparative information on pool frequency within an unmanaged sector. The maps were produced at a scale of 1:833 so that changes in the size of features of at least 2m magnitude can be recognized with confidence. Figure 5A to C illustrates three river sections (one in each of sectors B, D and C, respectively) mapped during the two surveys that show considerable change in channel morphology. Pools are mapped as discrete areas, whose change in location and size can be readily recognized between surveys. Thus comparisons were made between 1982 and 1996/97 in (i) the overall frequency of pools and changes in their size or area according to five classes (> 50 per cent larger, 25–50 per cent larger, no change greater than 25 per cent larger or smaller; 25–50 per cent smaller, > 50 per cent smaller) and (ii) the association between pools and LWD accumulations.

Frequency and size of pools

Table III provides within-sector reach median and mean values for various properties of pools and their dynamics. It also provides sector-based comparisons through the application of Kruskal–Wallis, non-parametric, Analysis of Variance (ANOVA). Table III includes information on the degree to which changes in pool frequency in sectors B, C, D and E between 1982 and 1996 were attributable to loss, gain, subdivision or amalgamation and the degree to which the pools observed in both 1982 and 1996 had changed in size between the two dates. Figure 6 illustrates the spacing between pools within 100m reaches of sectors B to E in 1982 and 1996, whereas Figure 7 illustrates changes in pool dimensions between 1982 and 1996.

Pool spacing, expressed in metres, increases in a downstream direction, but when expressed in units of channel width, the variation in pool spacing between 100m reaches and between sectors is greatly reduced (Figure 6, Table III). ANOVA (Table III) confirms that pool frequency per 100m was significantly greater in sector B than in C, D and E in 1982 and 1996/97. Reaches in sector A had a similar pool frequency to those in sector B in 1996/97, but because of the small sample of reaches in sector A, pool frequency was only statistically significantly greater ($P < 0{\cdot}05$) than in reach D. There was no significant difference in pool spacing, expressed in channel widths, in sectors B, D and E in 1982 (although spacing in sector C was significantly greater: median = 9·3, mean = 10·5 channel widths), but in 1996/97 spacing was significantly greater in both sectors C and D than in B.

Thus in the pre-disturbance situation, all sectors apart from the channelized C had a virtually identical average pool spacing of approximately four channel widths, but by 1996 the width-standardized pool spacing in the downstream sectors (particularly D) had increased in comparison with 1982. The pool spacing in sector A in 1997 was also greater than the expected four channel widths (median = 5·6, mean = 5·9 widths). However, this may be an artifact of data collection, being partly attributable to the scale problem of identifying pools of > 2m maximum dimension in a channel less than 2m wide. Analysis of the 46 reaches that contained debris dams in both 1982 and 1996/97 shows that although there is a decrease in the frequency of debris dams from sector A, B to D to E (Table II) when the frequency is scaled to channel width, there is no significant difference in debris dam spacing between the four sectors in either 1982 or 1996 (Table III). This is a further indication of the recovery in the total number of dams between the two surveys.

There are also major contrasts between sectors in the dynamics of the pools between 1982 and 1996/

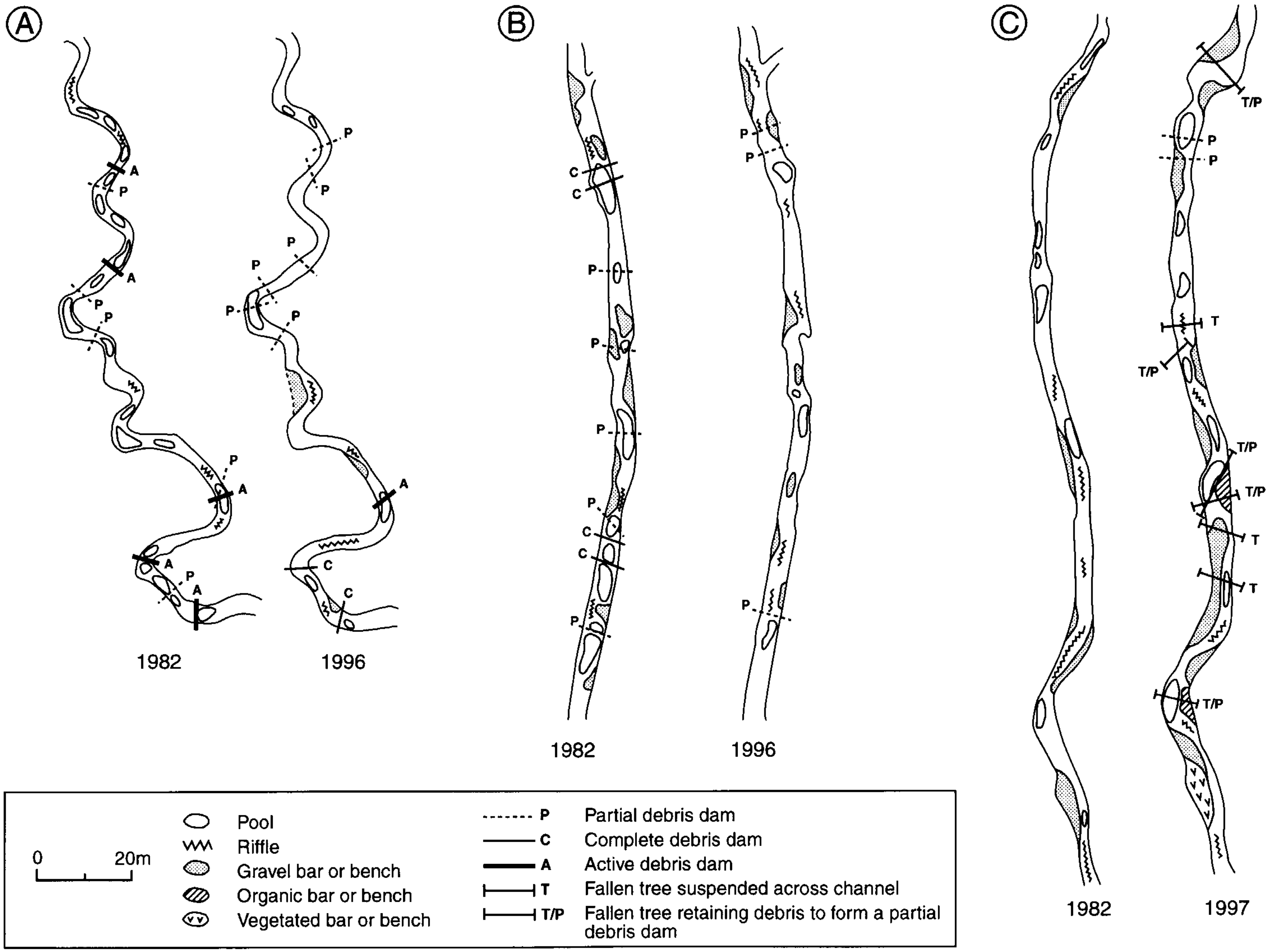

Figure 5. A comparison of geomorphological maps surveyed in 1982 and 1996/97 for a part of (A) sector B; (B) sector D; and (C) sector C.

Table III. Changes in the sector median (mean) frequency and spacing of pools, spacing of LWD dams, and dhcnages in pools, 1982 to 1996/97

	A		B		C		D		E		ANOVA*
No. 100 m reaches in sector	7		14		8		22		8		
No. pools/100 m 1982			13·0	(11·9)	5·0	(4·6)	7·0	(6·5)	5·5	(6·0)	B > D,E,C
No. pools/100 m 1996/97	10·0	(9·7)	11·5	(10·6)	4·5	(4·4)	4·0	(4·0)	5·0	(5·0)	B > E , C , D ; A > D
Pool spacing (widths) 1982			3·5	(4·1)	9·3	(10·5)	4·3	(4·3)	4·3	(4·1)	C > E,D,B
Pool spacing (widths) 1996/97	5·6	(5·9)	3·9	(4·5)	10.1	(11.6)	6.5	(7·9)	5·1	(5·9)	C,D > B
Dams spacing (widths) 1982†			6·0	(7·5)	–	–	6·9	(8·8)	8·8	(8·9)	‡
Dams spacing (widths 1996/97†	8·4	(8·6)	8·3	(7·3)	–	–	8·5	(9·9)	7·8	(6·4)	‡
Changes in pools between 1982 and 1996 as a proportion of total pools in 1982											
Pools unchanged in location and size			0·60	(0·56)	0·27	(0·24)	0·15	(0·16)	0·33	(0·28)	B > C,D
Pools lost			0·13	(0·14)	0·33	(0·37)	0·43	(0·44)	0·24	(0·26)	D > B
Pools reduced in area by > 25%			0·22	(0·24)	0·08	(0·37)	0·41	(0·36)	0·41	(0·41)	E,D > C
Pools reduced in area by > 50%			0·12	(0·13)	0·00	(0·09)	0·29	(0·29)	0·27	(0·27)	D > C
Pools gained			0·00	(0·01)	0·33	(0·40)	0·00	(0·07)	0·00	(0·01)	C > D,B,E
Pools increased in area by > 25%			0·00	(0·01)	0·17	(0·19)	0·00	(0·04)	0·00	(0·00)	C > E
Pools increased in area by > 50%			0·00	(0·01)	0·08	(0·17)	0·00	(0·03)	0·00	(0·00)	‡
Divided pools			0·00	(0·04)	0·00	(0·00)	0·00	(0·01)	0·00	(0·06)	‡
Combined pools			0·00	(0·00)	0·00	(0·05)	0·00	(0·00)	0·00	(0·00)	‡

Recent data sets analysed are from 1996 for sectors B, D and E from 1997 for sectors A and C
* Kruskal–Wallis non-parametric analysis of variance. Significant differences between sectors ($P < 0.05$) are listed where the overall ANOVA suggests that the samples (sectors) are drawn from different populations ($P < 0.05$)
† Sector C and five 100 m reaches of sectors D and E excluded because debris dams absent in 1982 and/or 1996
‡ No significant difference (P > 0·05) between sectors

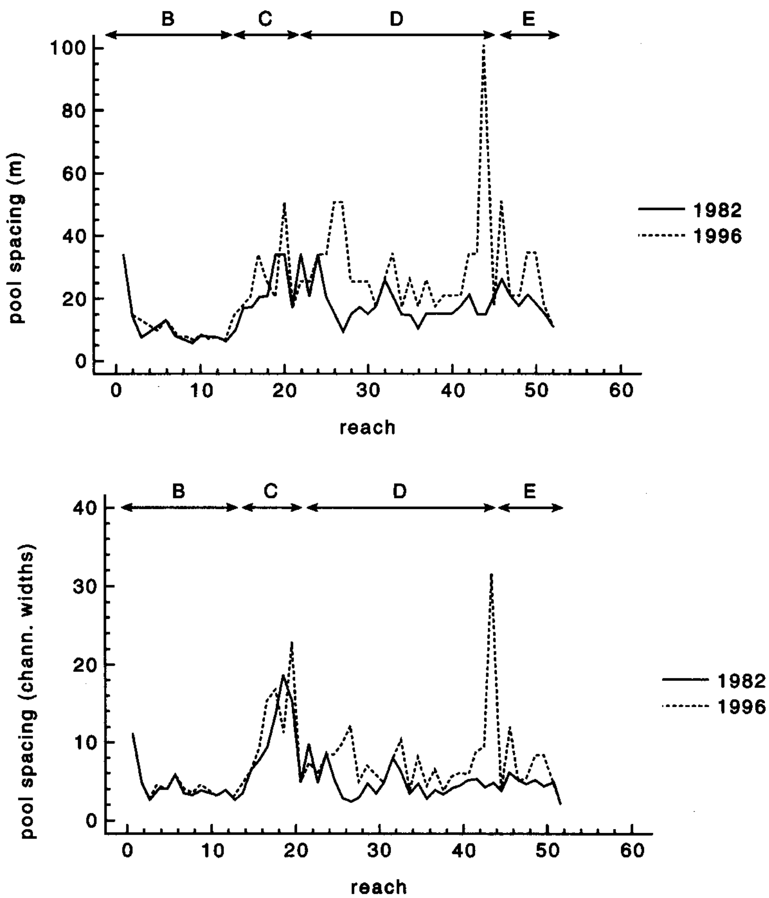

Figure 6. Pool spacing in each 100 m reach of sectors B, C, D and E in 1982 compared with 1996/97, expressed in metres (upper graph) and channel widths (lower graph)

97. Sector B had by far the largest proportion of 1982 pools that were unchanged in both location and size in 1996. Sector D suffered the greatest loss of pools (expressed as a proportion of the 1982 sector total of pools) and B the smallest loss. In addition, of pools which persisted from 1982 to 1996, a substantial reduction in size of pools occurred in sectors B, D and E. The proportion of pools affected by size reduction was greater in D and E (averages of 36 per cent and 41 per cent, respectively) than in B (24 per cent). Sector C was the only reach to undergo any notable increase in the size of pre-existing pools or to gain new pools between 1982 and 1996 (Figure 7).

Although there are no comparative observations of pool dynamics in the upstream control reach, where LWD has remained unmanaged, the reduction in the number and size of pools in sectors B, D and E has been marked, and the field evidence of sediment mobilization in sectors B, D and E but not in A is sufficiently clear, that much of the observed change seems very likely to be associated with debris dam removal. The particularly large changes in sector D, immediately downstream of sector C, suggest that erosion in sector C (induced by an increase in the slope as a result of channel straightening and a lack of LWD retention to dissipate flow energy and trap moving sediment), has further increased the sedimentation of downstream pools, particularly immediately downstream of sector C in sector D, where 44 per cent of 1982 pools have disappeared completely, 36 per cent have decreased in area, and 29 per cent have experienced more than a 50 per cent reduction in area. Although sector E has experienced a greater loss of pools and although a greater proportion of pools have decreased in area than in sector B,

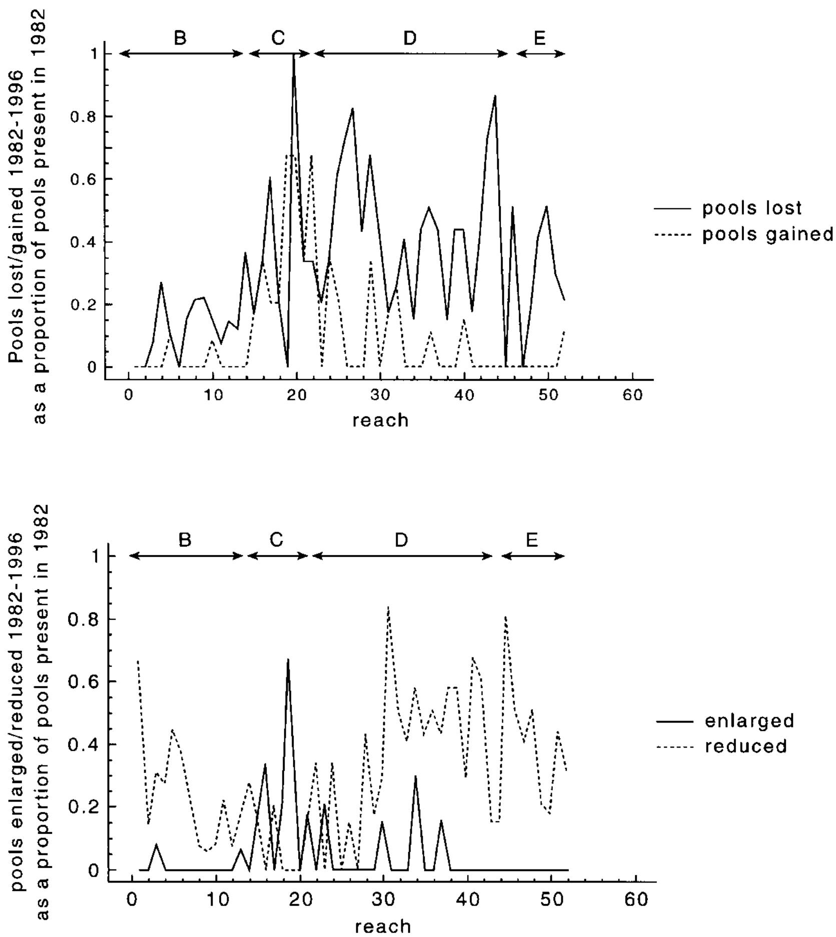

Figure 7. Pools lost or gained (upper graph) and enlarged or reduced in area by more than 25 per cent (lower graph) between 1982 and 1996, expressed as a proportion of 1982 pools in each 100 m reach of sectors B, C, D and E

the changes are less severe than in sector D. This suggests that the impact of erosion and transfer of sediment from sector C has had maximum impact on sector D and a lesser impact on sector E, whereas all three sectors (B, D and E) have experienced sedimentation of pools. In summary, although the association between channelization and enhanced sedimentation of downstream pools in sectors D and E is supported by the statistical analysis, it is, unfortunately, impossible to test statistically the significance of the apparent relationship between LWD dam removal and pool sedimentation in sectors B, D and E, because of the lack of a 1982 geomorphological map for the unmanaged sector A.

Associations between LWD accumulations and pools

To analyse the association between pools and LWD dams, pools were defined as proximate (at least a part of the pool located within one channel width of a LWD dam) or free (entire pool more than one channel width from the nearest LWD dam). This is similar to the distinction of self-formed and forced pools by Montgomery *et al.* (1995), where the latter were defined as being formed by scour around an

obstruction. The proximate dams were then subdivided into three subgroups according to their position with respect to the LWD dam: 'upstream', 'downstream' and 'at' (i.e. lateral to or extending beneath the dam). Frequencies of each type of pool were recorded for each 100 m reach of sectors A to E. Table IV lists the median and mean proportion of pools in each category in 1982 and 1996. In sectors A, B, D and E, there is a fairly similar proportion of proximate pools (the median ranges from 0·33 to 0·59 over both survey dates), with sectors B and D showing a decrease in the proportion of proximate pools between 1982 and 1996. The fairly even division of pools between proximate and free categories places the Highland Water on the transition between a pool–riffle and a forced pool–riffle channel as defined by Montgomery *et al.* (1995). Sector C has the lowest proportion of proximate pools, although there is an increase between 1982 and 1997 from 13 per cent to 24 per cent associated with the development of a small number of debris dams, particularly at the downstream end of the sector. Sector A has the highest proportion of proximate pools (median = 0·59). This may reflect the relatively unmanaged nature of the sector, but, it may in part, as already mentioned, result from the under-representation of free pools in this narrow channel. However, sector A has the largest number of proximate pools for each debris dam, indicating that the dam:pool association in the sector that has not been subject to LWD dam clearance is particularly strong.

Table V presents Spearman's rank correlations between pool and dam frequencies and channel width for the 52 reaches in sectors B to E. Correlations are similar for 1982 and 1996/97, and a number of patterns are identifiable. Total pool frequency is inversely correlated with channel width (a significant inverse correlation in 1996/97) and is highly positively correlated with total dam frequency. However, the strong association between dams and pools is better illustrated by three other features of Table V: (i) proximate pool frequency is the class of pool that is most highly correlated with total dam frequency; (ii) free pools have no significant correlation with dam frequency; and (iii) all subtypes of proximate pools are significantly correlated with dam frequency, whereas free pools are not significantly correlated with any subtype of dam. Thus the data for both 1982 and 1996 show a clear association between proximate pools and dams and a lack of association between free pools and dams.

The quantitative association between proximate pool frequency (Y) and total dam frequency (X) is illustrated by two simple regression relationships:

$$1982\text{:}\ Y = 0{\cdot}248 + 0{\cdot}778\ X\ (r^2 = 0{\cdot}757)$$
$$1996/97\text{:}\ Y = -0{\cdot}013 + 0{\cdot}661\ X\ (r^2 = 0{\cdot}661)$$

The slopes of these relationships are significantly different from zero and from one another ($P < 0{\cdot}05$), illustrating the smaller increment in proximate pools for each additional dam in 1996 and reflecting the loss of proximate pools between the two dates.

The above analyses show in a variety of ways that the presence of debris dams is associated with an increase in the frequency of pools. However, there must be an upper limit to the total number of pools that can exist within a 100 m reach, whether or not debris dams are present. Since pool frequency has been shown to vary with channel width, Figure 8 presents plots for 1982 and 1996/97 of the pool spacing in channel widths within the 52 reaches, against the number of dams in each reach. Figure 8 shows that in both 1982 and 1996/97, as dam frequency increases the pool spacing stabilizes at an average of approximately four channel widths. Figure 8 also illustrates that there is a minimum in the pool spacing that is observed in the Highland Water of approximately two channel widths regardless of the number of debris dams. This can be interpreted as the pool spacing that might be achieved throughout the Highland Water if the LWD remained undisturbed.

CONCLUSIONS

The results presented in this paper are derived from a single case study and their broader implications must be set within the context of the environmental characteristics of the study area. Four characteristics are particularly important. First, the study sectors occupy a headwater location, where the river channel is relatively narrow in comparison with the size of the riparian trees, and thus where a significant

Table IV. Median (mean) proportion of pools of different types within 100 m reaches of sectors B to E, 1982 and 1966

		A		B		C		D		E		ANOVA*
Proximate pools† (expressed as a proportion of the total number of pools in 1982 or 1996)												
Upstream	1982			0·11	(0·14)	0·00	(0·02)	0·14	(0·11)	0·10	(0·13)	‡
	1996/97	0·11	(0·14)	0·15	(0·17)	0·00	(0·04)	0·00	(0·11)	0·32	(0·30)	E > C
At dam:	1982			0·13	(0·17)	0·00	(0·02)	0·00	(0·10)	0·00	(0·07)	B > C
	1996/97	0·33	(0·32)	0·08	(0·08)	0·00	(0·15)	0·00	(0·05)	0·00	(0·05)	A > B,C,D,E
Downstream:	1982			0·20	(0·20)	0·00	(0·08)	0·17	(0·20)	0·20	(0·21)	‡
	1996/97	0·27	(0·22)	0·22	(0·22)	0·00	(0·05)	0·25	(0·21)	0·10	(0·15)	‡
Total proximate pools:	1982			0·50	(0·51)	0·00	(0·13)	0·41	(0·41)	0·40	(0·42)	B,E > C
	1996/97	0·59	(0·67)	0·43	(0·47)	0·20	(0·24)	0·33	(0·37)	0·45	(0·50)	A > D,C
Free pools§ (expressed as a proportion of the total number of pools in 1982 or 1996)												
1982				0·50	(0·49)	1·00	(0·80)	0·59	(0·59)	0·60	(0·58)	C > E,B
1996/97		0·41	(0·33)	0·57	(0·53)	0·80	(0·76)	0·67	(0·63)	0·55	(0·50)	C,D > A
Total pools/dam:	1982			1·7		6·2		1·8		2·2		¶
	1996/97	1·5		1·7		3·5		1·2		1·3		¶
Proximate pools/dam: 1982				0·9		0·8		0·8		0·9		¶
	1996/97	1·0		0·8		0·8		0·5		0·6		¶

* Kruskal–Wallis non-parametric analysis of variance. Significant differences between sectors ($P < 0{\cdot}05$) are noted where the overall ANOVA suggests that the samples (sectors) are not drawn from the same populations ($P < 0{\cdot}05$)

† Proximate pools are located (at least in part) within one channel width of a debris dam

‡ No significant difference ($P > 0{\cdot}05$) between sectors

§ Free pools are entirely located more than one channel width from the nearest debris dam

¶ Because there are individual reaches with no dams, these estimates are derived by dividing the total number of pools or proximate pools in each sector by the total number of dams in each sector. As a result of this method of calculation, contrasts between sectors cannot be analysed by analysis of variance.

Table V. Rank correlations between pool and dam frequencies within the 52 100 m reaches of sectors B to E, 1982 and 1996/97

	Width	Total dams	Partial	Complete	Active	Partial + active
1982						
Total pools	–0·226 NS	0·635 **	0·463 **	0·405 **	0·601 **	0·635 **
Total proximate	–0·113 NS	0·866 **	0·717 **	0·574 **	0·587 **	0·751 **
Upstream	–0·047 NS	0·623 **	0·531 **	0·419 **	0·337 *	0·511 **
At	–0·275 *	0·583 **	0·445 **	0·435 **	0·518 **	0·599 **
Downstream	–0·076 NS	0·723 **	0·573 **	0·437 **	0·549 **	0·632 **
Total free	–0·211 NS	–0·111 NS	–0·085 NS	–0·194 NS	0·106 NS	–0·054 NS
1996/97						
Total pools	–0·389 **	0·611 **	0·488 **	0·379 **	0·361 **	0·503 **
Total proximate	–0·182 NS	0·820 **	0·718 **	0·504 **	0·402 **	0·629 **
Upstream	0·009 NS	0·591 **	0·517 **	0·352 *	0·330 *	0·461 **
At	–0·303 *	0·267 NS	0·193 NS	0·186 NS	0·213 NS	0·261 NS
Downstream	–0·163 NS	0·680 **	0·626 **	0·383 **	0·317 *	0·483 **
Total free	–0·420 **	0·122 NS	0·025 NS	0·097 NS	0·127 NS	0·140 NS

** $P<0{\cdot}01$
* $P<0{\cdot}05$
NS, correlation not significantly different from zero

proportion of LWD is large enough to span the channel and so to form the framework around which active and complete debris dams can form. Second, the low gradient of the river system and the temperate nature of the local climate are important for the stability of LWD accumulations and thus their ability to retain sediment and regulate sediment transfer. In very steep headwater streams typical of mountainous areas, where extremely high intensity rain storms can also occur, entire sequences of debris dams can be destabilized by these extreme events to generate catastrophic debris torrents which cause massive erosion of extensive lengths of river channel. Third, the gravel-bed character of the channel has particular relevance for the retention and sorting of bed material around LWD accumulations. Indeed, the presence/absence/recovery of LWD accumulations has been shown to be strongly associated with pool spacing, and so appears to be a major influence on the pool–riffle sequences. Finally, the study area is predominantly under a deciduous woodland cover and, although it might be described as relatively unmanaged in a European context, it is heavily browsed by animals, and is subject to considerable human interference in comparison with the ‘old growth’ forests that have been studied in North America. It is this last characteristic which distinguishes the present study from many others, and yet this paper has shown that several of the properties of the LWD accumulations and their associated pools are similar to those reported by other researchers:

- Dam frequencies in sectors A, B, D and E are similar to those for third order streams (one to six per 100m) but are lower than those for second order streams (10 to 15 per 100m) observed in some North American studies (Gurnell *et al*., 1995).

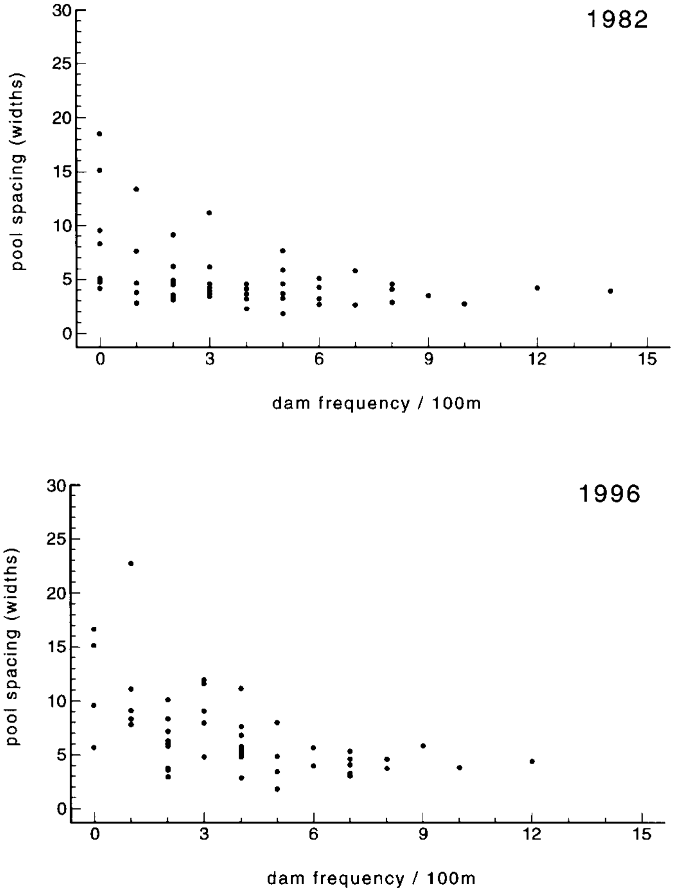

Figure 8. The relationship between pool spacing (in channel widths) and debris dam frequency in the 52 100 m reaches of sectors B, C, D and E in 1982 (upper graph) and 1996/97 (lower graph)

- The approximately equal proportion of proximate and free pools in sectors B, D and E places the Highland Water on the margin between a pool–riffle and forced pool–riffle channel (as defined by Montgomery *et al.*, 1995). The unmanaged (i.e. 1982) average pool spacing of *c.* four channel widths and the estimated minimum two channel width spacing on this 0·013 gradient, 1·8–4·5m width channel, compares favourably with the pool spacings of 3·7 and 2·7 widths on the 0·030, 0·016 gradient, 2·7, 4·0m width pool–riffle channels cited by Montgomery *et al.* (1995).

Some specific conclusions concerning the study area and the impact of its management can be highlighted from the analyses that have been presented:

- LWD accumulations have a similar spacing in sectors A, B, D and E in 1982 and 1996/97, when scaled by channel width. This suggests that the LWD retention capacity of these second and third order channels is more a function of local geomorphological features and of the riparian vegetation than of the channel planform. In contrast, the relatively recent channelization, incised channel form and younger plantation conifers of sector C do not promote efficient retention of LWD.
- LWD accumulations are dynamic when no management is undertaken, but LWD clearance results in greatly enhanced dynamism. Seven to eight years after clearance, the total number of dams had recovered to approximately pre-clearance levels but the hydraulically important complete and active dams had not recovered. Furthermore, recovery was achieved by high initial mobility in LWD to

establish unstable partial dams that were subsequently remobilized and reworked.

- Pools are closely associated with LWD dams of all types. As a result, channels containing LWD accumulations support a greater number of pools than those which are relatively free of LWD. Before LWD dam clearance, pools occurred at a median spacing of approximately four channel widths and, in the long term without debris clearance, might achieve a spacing of two channel widths. Of the pools that are closely associated with LWD, downstream (plunge) pools are the most frequent, indicating the importance of above-dam locations for sediment storage.
- LWD dam removal occurred in 1989. Pools in sectors B, D and E have undergone sedimentation between 1982 and 1996. This change has been interpreted as being partly a consequence of the release of sediment by dam removal, although lack of geomorphological maps for the control sector A in 1982 makes it impossible to test this assertion statistically. Sector C underwent channelization in *c*. 1966. Although erosion was observed prior to 1989, LWD clearance appears to have resulted in mobilization of this sediment. As a result, there is a high incidence of pool sedimentation downstream, particularly in the adjacent sector D. Thus seven to eight years after LWD clearance, the total number of dams has recovered to pre-clearance levels, but the pools have not recovered.

Management implications can be drawn from the above conclusions:

- Accumulations of LWD appear to have an important role in influencing the retention and regulated transfer of sediment in the study headwater stream. It appears that active and complete dam structures are particularly important in this regard, and that these structures, particularly active dams, take a long time to recover after destabilization by management. Active and complete dams accumulate mobile LWD pieces through time, so reducing the throughput of pieces that may cause management problems downstream, and becoming increasingly effective at retaining smaller pieces of organic material and mineral sediment. Older active dams often have a more complex interlocking structure than newer dams, particularly where they are constructed from pieces of deciduous trees such as oak and alder, which are typical of the study area and which have a more irregular form than LWD derived from conifers. All of these factors suggest that, wherever possible, major active and complete dams should not be disturbed, but should be left to evolve and stabilize into forms which will control local base levels, attenuate sediment and organic matter movement, and provide high physical habitat diversity to support a wide range of aquatic organisms both within and around the structures.
- Channelization, coupled with planting of young conifers in the mid-1960s, has resulted in severe erosion in one of the study sectors. Although this erosion and incision pre-dated dam clearance (the upstream migration of a knickpoint induced by channel bed incision was noticed within reach 13 of sector B in 1973), the consistent pool spacing of *c*. four channel widths in sectors B, D and E prior to debris dam clearance, suggests that the sediment produced was stored and routed through the system in a way which did not adversely affect pool spacing. The changes in downstream pool spacing and size since dam clearance indicate that sediment transfer rates from the eroding, channelized reach have been greatly increased as a result of LWD removal. This provides a further rationale for the maintenance of large active and complete LWD dams.
- The poor retention of LWD within channelized sector C may reflect low LWD input rates from the young trees. During the 1996/97 survey, it was apparent that LWD input was beginning to occur, but the conifers mainly input debris through tree fall. Entire trees bridge the channel whereas smaller debris pieces (which form a significant proportion of the input from deciduous woodland) are more likely to wedge within the channel. The vertical incision of the channel bed has made it increasingly difficult for debris to fall entirely or partly into the channel and so to provide a framework for debris dam development within this channelized sector. A possible management strategy would be to artificially introduce debris to construct stable dams. In one location (Figure 5C) the potential of such management is well illustrated by natural processes. Here, tree fall and bank failure have initiated the development of a more irregular channel planform which is more retentive and is beginning to accumulate LWD pieces and associated bars of organic and mineral sediment. Similar structures

introduced at other sites along this channelized sector would control bed incision and would attentuate sediment movement into the downstream sectors.

LWD accumulations appear to be a major control on the geomorphological character and dynamics of woodland streams. The frequency and type of LWD accumulation is important, but, to broaden the suggestion by Montgomery *et al.* (1995), pool spacing may also provide a useful summary index for assessing channel condition if it is evaluated in relation to the local potential for LWD loading and other flow obstructions and in the context of channel type, width and slope. Further studies of woodland streams are urgently required to establish guidelines for the management, enhancement and restoration of woodland river systems across the relatively disturbed European landscape which has so many contrasts with the areas of North America where most studies have been undertaken to date.

ACKNOWLEDGEMENTS

The Forestry Commission is gratefully acknowledged for permission to undertake research in the New Forest. This research builds upon a research programme that was co-directed by K. J. Gregory and A. M. Gurnell. R. Davis, N. Harris, K. Hewtson, C. Hill and S. Tooth assisted with different components of the pre-1996 data collection.

REFERENCES

Anderson, N. H. and Sedell, J. R. 1979. 'Detritus processing by macroinvertebrates in stream ecosystems', *Annual Review of Entomology,* **24**, 351–377.

Andrus, C. W., Long, B. A. and Froehlich, H. A. 1988. 'Woody debris and its contribution to pool formation in a coastal stream 50 years after logging', *Canadian Journal of Fisheries and Aquatic Sciences,* **45**, 2080–2086.

Angermeier, P. L. and Karr, J. R. 1984. 'Relationships between woody debris and fish habitat in a small warmwater stream', *Transactions of the American Fisheries Society,* **113**, 716–726.

Benke, A. C., Henry, R. L., Gillespie, D. M. and Hunter, R. J. 1985. 'Importance of snag habitat for animal production in Southeastern streams', *Fisheries,* **10**, 8–13.

Bilby, R. E. 1984. 'Removal of woody debris may affect stream channel stability', *Journal of Forestry,* **82**, 609–613.

Bisson, P. A. and Sedell, J. R. 1984. 'Salmonid populations in streams in clearcut vs. old-growth forests of Western Washington', in Meehan, W. R., Merrell, T. R. Jr and Hanley, T. A. (Eds), *Fish and Wildlife Relationships in Old-growth Forests: Proceedings of a Symposium*, American Institute of Fishery Research Biologists, 121–129.

Bisson, P. A., Nielson, J. L., Palmason, R. A. and Grove, L. E. 1982. 'A system for naming habitats types in small streams with examples of habitat utilisation by salmonids during low flow', in Armantrout, N. B. (Ed.), *Acquisition and Utilisation of Aquatic Habitat Inventory Information*, Western Division, American Fisheries Society, Portland, Oregon, 62–73.

Bisson, P. A., Bilby, R. E., Bryant, M. D., Dolloff, C. A., Grette, G. B., House, R. A., Murphy, M. L., Koski, K. V. and Sedell, J. R. 1987. 'Large woody debris in forested streams in the Pacific Northwest: Past, present and future', in Salo, E. O. and Cundy, T. W. (Eds), *Streamside Management: Forestry and Fishery Interactions*, College of Forest Resources, University of Washington, Contribution, **57**, 143–190.

Brookes, A. 1995. 'Challenges and objectives for geomorphology in U.K. river management', *Earth Surface Processes and Landforms,* **20**, 593–610.

Ehrman, T. P. and Lamberti, G. A. 1992. 'Hydraulic and particulate matter retention in a 3rd-order Indiana stream', *Journal of the North American Benthological Society,* **11**, 341–349.

Gregory, K. J. 1992. 'Vegetation and river channel process interactions', in Boon, P. J., Calow, P. and Petts, G. E. (Eds), *River Conservation and Management*, Wiley, Chichester, 255–269.

Gregory, K. J. and Davis, R. J. 1992. 'Coarse woody debris in stream channels in relation to river channel management in woodland areas', *Regulated Rivers: Research and Management,* **7**, 117–136.

Gregory, K. J., Gurnell, A. M. and Hill, C. T. 1985. 'The permanence of debris dams related to river channel processes', *Hydrological Sciences Journal,* **30**, 371–381.

Gregory, K. J., Davis, R. J. and Tooth, S. 1993. 'Spatial distribution of coarse woody debris dams in the Lymington Basin, Hampshire, UK', *Geomorphology,* **6**, 207–224.

Gregory, K. J., Gurnell, A. M., Hill, C. T. and Tooth, S. 1994. 'Stability of the pool–riffle sequence in changing river channels', *Regulated Rivers,* **9**, 35–43.

Gurnell, A. M. and Gregory, K. J. 1995. 'Interactions between semi-natural vegetation and hydrogeomorphological processes', *Geomorphology,* **13**, 49–69.

Gurnell, A. M., Gregory, K. J. and Petts, G. E. 1995. 'The role of coarse woody debris in forest aquatic habitats: implications for management', *Aquatic Conservation,* **5**, 143–166.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S. V., Lattin, J. D., Anderson, N. H., Cline, S. P., Aumen,

N. G., Sedell, J. R., Lienkaemper, G. W., Cromack, K. and Cummins, K. W. 1986. 'Ecology of coarse woody debris in temperate ecosystems', *Advances in Ecological Research,* **15**, 133–302.

Harvey, J. W. and Bencala, K. E. 1993. 'The effect of streambed topography on surface–subsurface water exchange in mountain catchments', *Water Resources Research,* **29**, 89–98.

Hedin, L. O., Mayer, M. S. and Likens, G. E. 1988. 'The effect of deforestation on organic debris dams', *Verh. Internat. Verein. Limmol.,* **23**, 1135–1141.

Heede, B. H. 1985. 'Channel adjustments to the removal of log steps: an experiment in a mountain stream', *Environmental Management,* **9**, 427–432.

Hickin, E. J. 1984. 'Vegetation and river channel dynamics', *Canadian Geographer,* **28**, 111–126.

Hogan, D. L. 1986. *Channel morphology of unlogged and debris torrented streams in the Queen Charlotte Islands*, British Columbia Ministry of Forests and Lands, Land Management Report No. **49**, 94 pp.

Keller, E. A. and Swanson, F. J. 1979. 'Effects of large organic debris on channel form and fluvial process', *Earth Surface Processes,* **4**, 361–380.

Keller, E. A. and Talley, T. 1979. 'Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment', in Rhodes, D. D. and Williams, G. P. (Eds), *Adjustments of the Fluvial System*, Proceedings of the 10th Annual Geomorphology Symposium, Kendell/Hunt, New York, 169–197.

Leopold, L. B. and Wolman, M. G. 1957. *River channel patterns: Braided, meandering and straight*, US Geological Survey Professional Paper **282-B**, 85pp.

Leopold, L. B., Wolman, M. G. and Miller, J. P. 1964. *Fluvial Processes in Geomorphology*, W. H. Freeman, New York, 522pp.

Lisle, T. E. 1981. 'Roughness elements: a key resource to improve anadromous fish habitat', in Hassler, T. J. (Ed.), *Proceedings of the propagation, enhancement and rehabilitation of anadromous salmonid populations and habitat in the Pacific Northwest Symposium*, Humboldt State University, Arcata, California, 93–98.

MacDonald, A., Keller, E. A. and Talley, T. 1982. 'The role of large organic debris on stream channels draining redwood forests northwestern California', in Harden, D. K., Marran, D. C. and MacDonald, A. (Eds), *Late Cenzoic History and Forest Geomorphology of Humbold Co. California*, Friends of the Pleistocene, Pacific Cell fieldtrip guidebook, 226–245.

Marston, R. A. 1982. 'The geomorphic significance of log steps in Forest streams', *Annals of the Association of American Geographers,* **72**, 99–108.

Marzolf, G. R. 1978. *The potential effects of clearing and snagging on stream ecosystems*, Biological Services Program, **FWS/OBS-78/14**, Fish and Wildlife Service, US Department of the Interior, 31pp.

Maser, C. and Sedell, J. R. 1994. *From the Forest to the Sea: the ecology of wood in streams, rivers, estuaries, and oceans*, St Lucie Press, Florida.

Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M. and Press, G. 1995. 'Pool spacing in forest channels', *Water Resources Research,* **31**, 1097–1105.

Nakamura, F. and Swanson, F. J. 1993. 'Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon', *Earth Surface Processes and Landforms,* **18**, 43–61.

Piégay, H. and Gurnell, A. M. 1997. 'Large woody debris and river geomorphological pattern: examples from S. E. France and S. England', *Geomorphology,* **19,** 99–116.

Robinson, E. G. and Beschta, R. L. 1990a. 'Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA', *Earth Surface Processes and Landforms,* **15**, 149–156.

Robinson, E. G. and Beschta, R. L. 1990b. 'Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA', *Canadian Journal of Aquatic Science,* **47**, 1684–1693.

Scrivener, J. C. and Anderson, B. C. 1984. 'Logging impacts and some mechanisms that determine the size of spring and summer populations of coho salmon fry (*Oncorhynchus kisutch*) in Carnation Creek, British Columbia', *Canadian Journal of Fish and Aquatic Science*, **41**, 1097–1105.

Smith, R. D. and Beschta, R. L. 1994. 'A mechanism of pool formation and maintenance in forest streams', *Hydraulic Engineering'94*, Proceedings of conference sponsored by the Hydraulics Division, ASCE, 824–828.

Smock, L. A., Gladden, J. E., Riekenberg, J. L., Smith, L. C. and Black, C. R. 1992. 'Lotic macroinvertebrate production in three dimensions: channel surface, hyporheic, and floodplain environments', *Ecology,* **73**, 876–886.

Sullivan, K., Lisle, T. E., Dolloff, C. A., Grant, G. E. and Reid, L. M. 1987. 'Stream channels: the link between forests and fishes', in Salo, E. O. and Cundy, T. W. (Eds), *Streamside Management: Forestry and Fishery Interactions*, College of Forest Resources, University of Washington, 39–97.

Thibodeaux, L. J. and Boyle, J. D. 1987. 'Bedform-generated convective transport in bottom sediment', *Nature,* **325**, 341–343.

Ward, G. M. and Aumen, N. G. 1986. 'Woody debris as a source of fine particulate matter in coniferous forest stream ecosystems', *Canadian Journal of Fisheries and Aquatic Sciences,* **43**, 1635–1642.

Ward *et al*., 1995. *The New Rivers and Wildlife Handbook*, RSPB.

Wharton, G. 1995. 'Information from channel geometry – discharge relations', in Gurnell, A. M. and Petts, G. E. (Eds), *Changing River Channels*, Wiley, Chichester, 325–346.

Winkler, G. 1991. 'Debris dams and retention in a low order stream (a backwater of Oberer Seebach – Ritrodat – Lunz study area, Austria)', *Internationale Vereinigung fur theoretische und angewandte Limnologie*, Proceedings of the Munich Congress, **24**(3) 1917–1920.

Wood-Smith, R. D. and Buffington, J. M. 1996. 'Multivariate geomorphic analysis of forest streams: Implications for assessment of land use impacts on channel condition', *Earth Surface Processes and Landforms,* **21**, 377–393.

